# APPARATUS AND ASSOCIATED METHODS

## TECHNICAL FIELD

[0001] The present disclosure relates to the field of metal-insulator-metal (MIM) diodes, associated methods and apparatus, and in particular concerns a graphene-based MIM diode which may be used in photodetectors and rectennas. Certain disclosed example aspects/embodiments relate to portable electronic devices, in particular, so-called hand-portable electronic devices which may be hand-held in use (although they may be placed in a cradle in use). Such hand-portable electronic devices include so-called Personal Digital Assistants (PDAs).

[0002] The portable electronic devices/apparatus according to one or more disclosed example aspects/embodiments may provide one or more audio/text/video communication functions (e.g. tele-communication, video-communication, and/or text transmission, Short Message Service (SMS)/Multimedia Message Service (MMS)/emailing functions, interactive/non-interactive viewing functions (e.g. web-browsing, navigation, TV/program viewing functions), music recording/playing functions (e.g. MP3 or other format and/or (FM/AM) radio broadcast recording/playing), downloading/sending of data functions, image capture function (e.g. using a (e.g. in-built) digital camera), and gaming functions.

## BACKGROUND

[0003] MIM diodes have previously been fabricated using thermal or plasma oxidation of crystalline metal films. Diodes fabricated in this way, however, exhibit poor yield and performance. To a large extent, these problems can be attributed to the roughness of the metal surface, which is often greater than the thickness of the insulator. The roughness of the metal results in a non-uniform electric field across the device, which makes it difficult to control the electron tunnelling.

[0004] Recently, the use of an amorphous metal layer has been proposed for reducing surface roughness in MIM devices. The proposed material, however, is an alloy (ZrCuAlNi) consisting of four metals, which increases the complexity and cost of fabrication.

[0005] Furthermore, such alloys are not suitable for use in flexible and transparent electronics because the material is opaque and relatively brittle.

[0006] The apparatus and methods disclosed herein may or may not address this issue.

[0007] The listing or discussion of a prior-published document or any background in this specification should not necessarily be taken as an acknowledgement that the document or background is part of the state of the art or is common general knowledge. One or more aspects/embodiments of the present disclosure may or may not address one or more of the background issues.

## SUMMARY

[0008] According to a first aspect, there is provided an apparatus comprising first and second layers of electrically conductive material separated by a layer of electrically insulating material, wherein one or both layers of electrically conductive material comprise graphene, and wherein the apparatus is configured such that electrons are able to tunnel from the first layer of electrically conductive material through the layer of electrically insulating material to the second layer of electrically conductive material.

[0009] The apparatus may be configured such that electrons are unable to tunnel from the second layer of electrically conductive material through the layer of electrically insulating material to the first layer of electrically conductive material by virtue of providing a difference in voltage to the first and second layers of electrically conductive material, and/or providing a difference in work function between the first and second layers of electrically conductive material.

[0010] The first and second layers of electrically conductive material may be made solely from graphene. The first layer of electrically conductive material may comprise graphene, and the second layer of electrically conductive material may comprise one or more of Cr, Au, Al, Ni, Cu, Pt, W, and indium tin oxide or an alloy comprising one or more of the same. The second layer of electrically conductive material may comprise one or more nanopillars.

[0011] The layer of electrically insulating material may comprise one of $Al_2O_3$, $HfO_2$, BN and diamond-like carbon. The layer of electrically insulating material may have a thickness of no greater than 15 nm, possibly 5-10 nm, which can be extended to 5-15 nm just in case strong biases are to be used. The thickness of the oxide can be considered to be critical for proper tunnelling. It can not be too thick, but it can not be too thin either or a different type of full-barrier tunnelling (bias-independent) will take place.

[0012] One or more of the first layer of electrically conductive material, the second layer of electrically conductive material and the layer of electrically insulating material may be optically transparent. The expression "optically transparent" may be taken to mean transparent to one or more different types of electromagnetic radiation (e.g. UV, IR, visible light, microwave, radio, or X-rays), rather than just transparent solely to visible light.

[0013] The apparatus may be formed on a supporting substrate. The supporting substrate may be electrically insulating. The supporting substrate may be optically transparent. The supporting substrate may comprise glass or oxidised silicon.

[0014] The apparatus may comprise a passivation layer on top of the uppermost layer of electrically conductive material (i.e. the first or second layer of electrically conductive material depending on the fabrication process used to form the apparatus).

[0015] The apparatus may comprise a voltage source. The voltage source may be configured to apply a potential difference between the layers of electrically conductive material to facilitate the tunnelling of electrons from the first layer of electrically conductive material through the layer of electrically insulating material to the second layer of electrically conductive material, and impede the tunnelling of electrons from the second layer of electrically conductive material through the layer of electrically insulating material to the first layer of electrically conductive material. The voltage source may be configured to apply a negative potential to the first layer of electrically conductive material and/or a positive potential to the second layer of electrically conductive material.

[0016] The electrons may be hot electrons generated when the first layer of electrically conductive material is illuminated by electromagnetic radiation (e.g. UV, IR, visible light, microwave, radio, or X-rays). The apparatus may comprise a source of electromagnetic radiation configured to illuminate the first layer of electrically conductive material with electromagnetic radiation in order to generate the hot electrons.